Finite Element Modeling of Heat Transfer Modes in Local Gap Formation During Solidification of Cast Components
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Abstract. In the casting process, there is the casting and the mold. Due to the temperature difference between these two parts and the fact that materials present physical deformations due to this temperature variation, there is the phenomenon of the appearance of gaps between the components. This work then aims to analyze the influence of how the development of these gaps occurs during solidification, on the resulting local cooling curves of the casting. Using a finite element software, different simulations were performed that show different approaches to the evolution of the process, considering different plots and behaviors of the heat transfer phenomena - conduction, radiation, convection. Through the study and correct definition of the model parameters, the outputs generated by the program were observed and evaluated in graphic and tabular form, confirming the possibility of analyzing the piece locally, with satisfactory results regarding the general aspect of the heat exchange phenomena and gap formation involved in the process.

Keywords: casting, colling rate, finite element, heat transfer, heat transfer coefficient.

1 Introduction

Casting is a manufacturing process widely spread around the world, it is a method of obtaining parts with specific geometry and properties by pouring the molten material into a mold, where then the material will solidify into the shape proposed by the existing mold and then result in the object with the desired form [1].

One of the phenomena that occur during the process is the appearance of air gaps between the part and the mold [2]. During solidification, the molten material is subjected to a large temperature variation, which also results in physical effects, such as the variation of its geometry and the appearance of residual stresses arising from the shrinkage of the material. This variation in geometry occurs since the mold is at a lower temperature and the casting is at a higher temperature [3], so according to the Law of Thermal Expansion, the part will contract, and the mold will expand. The relative motion between the components generates gaps, or spaces, between them at certain points along their geometries, affecting the type of heat transfer predominant in the process.

At the beginning of the process, heat transfer takes place in the 3 existing modes, being convection, radiation, and predominantly conduction. However, each of the modes needs prerequisites to happen and in the case of conduction, it is essential that there is a contact for the heat to spread. According to [4], with the appearance of the gap at certain points of the parts, there is a change of heat exchange at points without contact to convection and radiation modes, while at points with contact, conduction remains present.

This change in heat transfer mode changes the magnitude of the transfer, which is considerably greater with conduction, causing a temperature gradient to appear across the part. The temperature gradient promotes, besides the change in material properties (because most of the material specific coefficients are temperature dependent), the increase in residual stress [5], due to the difference in thermal stresses along the length, which can be extremely detrimental to the future performance of the component and undesirable geometric distortions, which escape the pre-established geometric tolerances of production quality of the final product. In addition, the existence of contact and non-contact regions creates uncertainty about the magnitude of the force required at the end of the process to remove the finished cast part from the mold [6]. Which can be harmful, as the misused force could damage the finished part.

Thus, for casting processes, where the mechanical and thermal phenomena present contain a specific associated complexity, the application of the finite element method is important for the thorough analysis of the process [7]. This method is a computational tool widely used in almost all engineering situations. Based on numerical-computational models for solving real problems, commercial finite element software solves problems that are not possible to solve manually [8].

2 Methodology

The case studied in this paper is a casting process, considering specific geometry and materials, in order to understand the transient and non-linear behavior in the heat exchange process during manufacturing. The layout of the studied process consisted of two different parts, called mold and casting (Figure 1). This geometry was chosen precisely because the thermal expansion generated in the part is expected to behave differently along the geometry, consequently leading to different heat fluxes and temperature gradients.

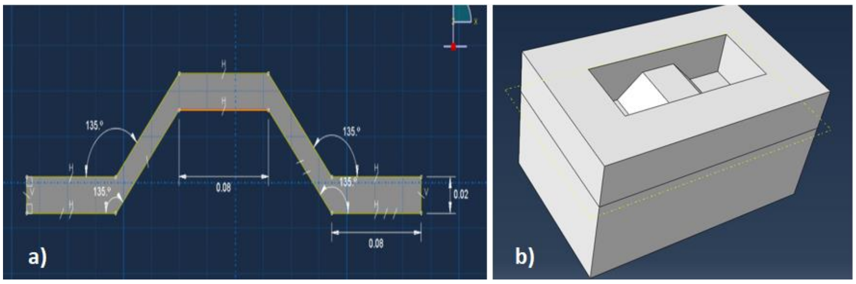


Figure 1. a) Casting Part’s Geometry. b) Mold’s Geometry.

The component is made of the aluminum alloy A356 (Al-Si7Mg), a material that is usually manufactured by casting. The mold has the cavity of the casting shape and elongated geometry at the bottom for fixing. The material used to represent the mold is Steel 1.2343 (X37CrMoV5-1), a material widely used in permanent mold casting processes. The material properties were provided mostly temperature dependent.

2.1 Simulation Step

The simulations are divided into three different situations. They differ in how heat is exchanged between the mold and the casting. The first stage acts only with the heat exchange by conduction with a fixed valued of heat transfer coefficient, the second stage works the same way, but with the heat coefficient varying with the clearance between the parts. The third stage uses the second stage model, but with addition of radiation from the beginning of the process. This case would be the closest to reality, except for adding the phenomenon of convection. However, for reasons of simplification and lack of knowledge regarding factors such as the convection coefficients of the surfaces, it was neglected.

The software used was Abaqus 2016, as it presents good results in studies related to the casting area such as [3] and [4]. Within the software, the modeling and simulation process is basically divided into 7 parts: Part, Material, Section, Mesh, Assembly, Step, and Job. The first part involves only the drawing of the components, already described above.

In the next section of the model, the materials that will be applied to the parts are created. Thermal, mechanical, and electrical properties can be inserted, according to the user's needs. All material properties were inputted directly into the software, without the need to create subroutines to describe specific behaviors or to use other constitutive mechanical and thermal laws in place of the laws in use by the software, shown below.

Thermal	**Mechanical**
$\rho\left(\frac{\partial H(T)}{\partial T}\right)\left(\frac{\partial T}{\partial t}\right)=\frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k(T)\frac{\partial T}{\partial y}\right)$ (General law for heat exchange)	$\{\Delta\sigma\} = [D]\{\Delta\varepsilon_e\} + [\Delta D]\{\varepsilon_e\}$ (General law of stress and strain)
$q = -kA\frac{\partial T}{\partial x}$ (Conduction equation)	$\{\sigma\} = \{\sigma_x \quad \sigma_y \quad \sigma_z \quad \tau_{xy}\}^T$ (Stress vector)
$q = -hA(T_\infty - T_s)$ (Convection equation)	$\{\varepsilon\} = \{\varepsilon_x \quad \varepsilon_y \quad \varepsilon_z \quad \varepsilon_{xy}\}^T$ (Strain vector)
$q = \varepsilon A\sigma(T_1^4 - T_2^4)$ (Radiation equation)	$[D] = \frac{E(T)}{(1+\nu)(1-2\nu)}\begin{bmatrix} 1-\nu & \nu & 0 & \nu \\ \nu & 1-\nu & 0 & \nu \\ 0 & 0 & \frac{1-2\nu}{2} & 0 \\ \nu & \nu & 0 & 1-\nu \end{bmatrix}$ (Hooke's law)

Table 1. Constitutive Laws

Once the material has been created, it needs to be assigned to a section that has been created and that section is assigned to the geometry. At this stage, both sections created were solid, homogeneous and with the associated material. After the sections are created, a spatial mesh is generated for the components (Figure 2). The mesh is a finitesimal division of the geometry into parts of a predefined shape and the equations governing the problem will be calculated at its nodes. On the one hand, the mesh needs to be refined enough to represent the geometry as widely as possible, on the other hand, after a certain point, even with the increasing refinement of the mesh, it will represent equal results.

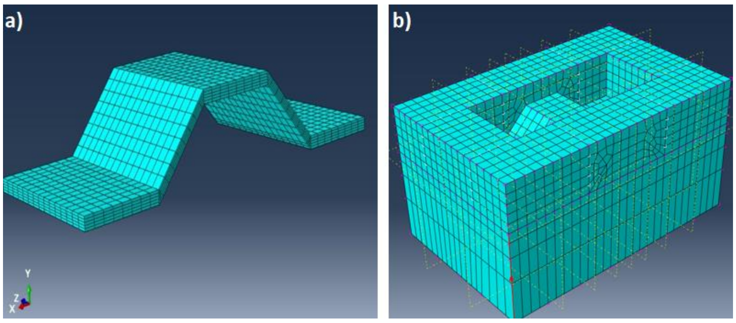
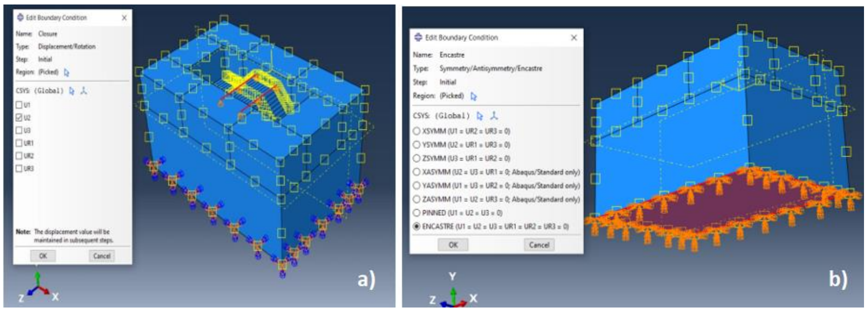


Figure 2. a) Casting Part's Mesh. b) Mold's Mesh.

The phase after mesh selection is where the different components created will be assembled together. For this work, the casting part is simply attached to the mold cavity. Subsequently, the step-by-step creation of how the simulation will proceed is necessary. For this process, the Coupled Temperature-Deformation type was chosen, and there are no mechanical or thermal loads on the parts since the heat exchange and deformation process occur due to the initial condition of the system itself. These initial conditions were defined as follows:

- The casting part has an initial temperature of 700°C and remains fixed in the mold with the restriction of movement in the vertical axis at the two top edges (Figure 3a), just to ensure isostaticity;

- The mold is at an initial temperature of 20°C and fixed to the ground on its bottom surface (Figure 3b).



Name: Closure
Type: Displacement/Rotation
Step: Initial
Region: (Picked)
CSYS: (Global)
☐ U1
☑ U2
☐ U3
☐ UR1
☐ UR2
☐ UR3
Note: The displacement value will be maintained in subsequent steps.

Name: Encastre
Type: Symmetry/Antisymmetry/Encastre
Step: Initial
Region: (Picked)
CSYS: (Global)
○ XSYMM (U1 = UR2 = UR3 = 0)
○ YSYMM (U2 = UR1 = UR3 = 0)
○ ZSYMM (U3 = UR1 = UR2 = 0)
○ XASYMM (U2 = U3 = UR1 = 0; Abaqus/Standard only)
○ YASYMM (U1 = U3 = UR2 = 0; Abaqus/Standard only)
○ ZASYMM (U1 = U2 = UR3 = 0; Abaqus/Standard only)
○ PINNED (U1 = U2 = U3 = 0)
● ENCASTRE (U1 = U2 = U3 = UR1 = UR2 = UR3 = 0)

Figure 3. Mechanical Constraints on (a) Casting Part (b) Mold.

What differentiates the three models created is the definition of the thermal iterations. For the first case, the conduction is defined as having a coefficient 50000 W/m²K, throughout the process, and it is defined with respect to the gap between the components. According to [5] for Aluminum casting processes, values reach up to 60000 W/m²K, so 50000 W/m²K was chosen as an assumption to perform the analyses.

For the second case, a tabular description of the values of the heat conduction coefficient was created (Figure 4). This value was chosen considering that [9] state that from 0.05mm of space between the workpieces, the gap starts to have a significant effect on the thermal process. However, the value of 0.05mm, generated processing complications in the software and due to this then the value of 0.1mm was chosen.

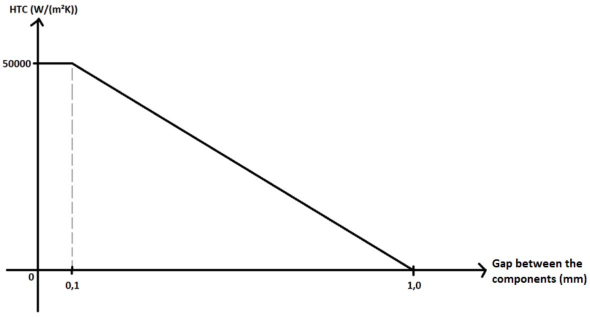


Figure 4. Behavior of the Conduction Coefficient in Case 2.

The third case presents the addition of radiation. The Radiation is expelled from the entire casting part, the emissivity is set to a value of 0.3 and the ambient temperature 20°C. For this specific situation, simulations were additionally performed with the same mesh, where they were divided into 5 new cases, with the emissivity of 0.1, 0.3, 0.5, 0.7 and 0.9 respectively, in order to observe the effects of the change in the value of this property on the process. After creating the interactions, it was chosen the total process time as 100 s, according to an estimate of how long casting processes last on parts of this size at the Institute of Joining and Welding Techniques at the Technische Universität Braunschweig and the other time discretization configurations. The most critical values to choose are the minimum value and the initial value. The former quoted needs to be small enough to ensure convergence and the latter, if estimated as close as possible to how the initial behavior of the increments will be, saves computational cost. The output variables aimed to be analyzed are the geometric displacement and temperature variation along time and geometry.

3 Results and Discussions

3.1 Process Simulation

Considering the equations that govern the problem, it is expected that for the first model, the cooling curve of the casting is the steepest, because there is a constant heat exchange by conduction until the end of the process, without any decrease in heat exchange due to the emergence of gaps. This means that for the established range of process simulation, the casting part should have a cooling curve with a steeper drop than the other models, evidencing a higher heat rate. In addition, since the cooling will happen faster and the thermal exchange will be maintained for longer, due to the non-importance of the lack of contact between the parts, the Gap generated should be the largest among the three models.

The resulting curves and patterns generated by the Software follow what is expected for a solidification process with the addition of the mechanical part, therefore, of displacements. The Plateau that represents the heat exchange being used as Latent energy for solidification is also observed (Figure 5). Besides the solidification validation, the curves of all models showed the sharpest initial temperature drop, which can be explained because at the beginning of the process the temperature difference between the parts is greater, thus the heat transfer is more intense. As the process progresses, the temperature of the aluminum component decreases, while that of the steel component increases, in order to reach thermal equilibrium.

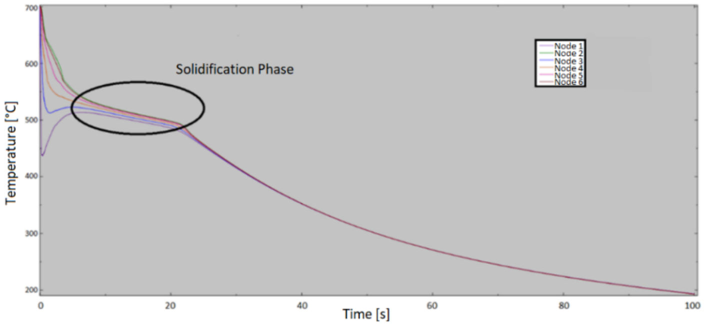


Figure 5. Example of Model 1 Nodes Cooling Curves.

For Model 2 as there is deformation of the parts and consequently the creation of gaps between them, there should be no more thermal exchange by conduction. Therefore, the cooling curve for Model 2 is estimated to be the slowest, i.e., as conduction has decreased, and there is still no contribution from radiation, the materials only exchange heat at points where even with deformation, there is still contact (Figure 6). These points naturally present far fewer area of heat exchange than if contact was considered over the entire surface, and as the heat flux depends on the area, the smaller it is, the lower the flux will be.

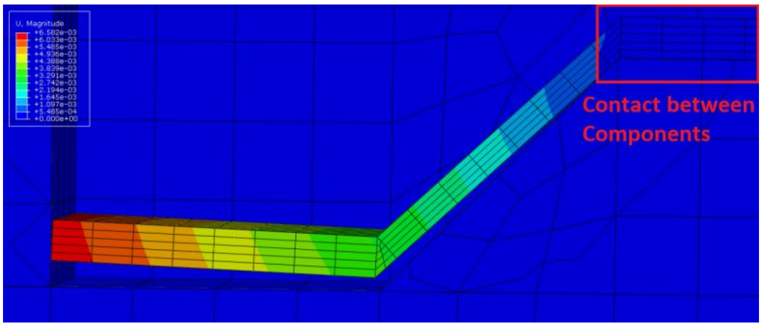


Figure 6. Contact Region even after the Process.

In Model 3, for the solution of radiation problems, the software performs a non-linear type of simulation, due to the 4° degree of the equation. Even so, it was not observed a great change between the process times of the simulations, being the first the fastest and the third the longest, but all between 55min and 1h05min. With the insertion of radiation in the program, it was possible to observe and confirm the hypotheses. The cooling curves present the same behavior, having three areas of emphasis, which are: initial sharp drop in temperature, a region approximately constant, and a smoother final drop (Figure 7). Model 1 presented the most accelerated cooling curve, followed by Model 3, and finally Model 2, which suggests that the models followed the physical logic regarding the thermal exchange parcels.

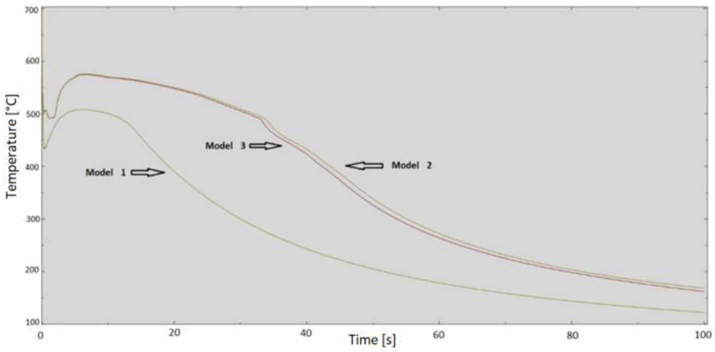


Figure 7. Comparison of Cooling Curves of the 3 Models: Node with Gap Generation.

The chosen node, whose curve is shown in Figure (7), is located in an area where deformation occurs more pronouncedly, so that contact no longer exists. To confirm the effects of the gap in heat exchange, Figure (8) shows the cooling curve for a Node present on the bottom surface of a region where contact exists even after the process (region evidenced in Figure 6), and it can be seen that the difference in the curves is not so noticeable.

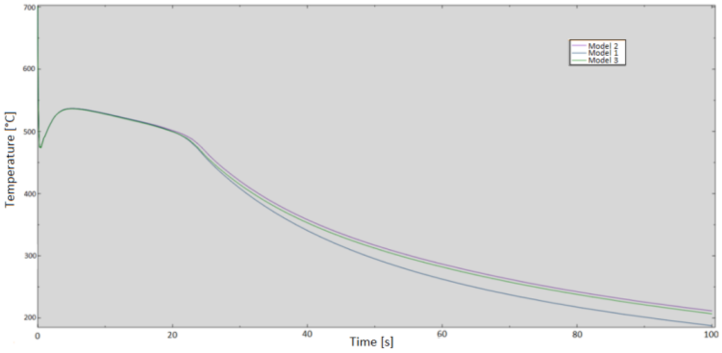


Figure 8. Comparison of Cooling Curves of the 3 Models: Node with no Gap Generation.

Regarding the mechanical part of the simulation, it is possible to perform the analysis of the values of deformations (gaps) generated in the process. The maximum values of the gap were observed at the same location for all models and are found at the edges of the casting. This difference in deformation values can be seen in Figure 9, in which the maximum gap values of 6mm, 6.2mm, and 6.6mm are shown for models 2, 3, and 1, respectively, following what is expected regarding the relationship between heat transfer and gap magnitude.

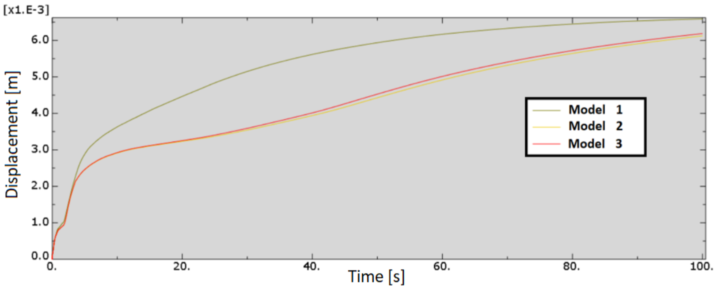


Figure 9. Gap Development Comparison.

3.2 Effect of Emissivity

To analyze the effect on the variation of the emissivity of the part, five simulations were performed, based on the definitions of the third model, varying the emissivity to values of 0.1, 0.3, 0.5, 0.7 and 0.9. Besides the advantage of observing the effects of this factor and as emissivity is a coefficient dependent on several parameters, one of them being the temperature at which the material is, the most realistic would be to set a range of values for it, rather than a single fixed value. The biggest difference between the curves is between the values for the emissivity of 0.1 and 0.9, respectively, occurring after the solidification of the aluminum. The curves also represent the behavior of the radiation formula, showing that increasing the emissivity, will increase the heat transfer, hence the cooling velocity. It can be seen in Figure (10) also that the course of the gap developed is the same for this case considered, with only changes in the values.

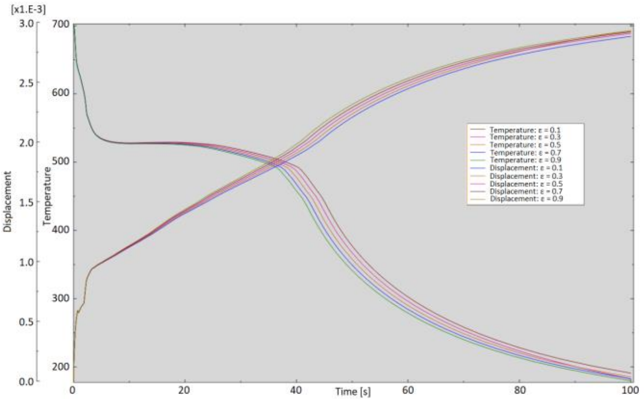


Figure 10. Development of the Gap and Cooling Curve for the 5 Emissivities.

4 Conclusions

The overall appearance of the data extracted from the simulations was very satisfactory and proved the hypotheses raised earlier in the process, showing that the models followed the expected behavior. The model responded properly to what was expected regarding the more accurate local calculation of HTC and the practical consequences of considering the development of the gap and the radiation portion in the cooling curve of the part. The significant difference in HTC values is proof that the different methods of evaluating the situation influence the process as a whole and consequently the final part produced.

Furthermore, the results help to better understand the process as a whole and highlight the importance of prior analysis of the different heat transfer methods to ensure the final characteristics of the part, hence, the quality of the final product obtained. It is worth pointing out that the work is done with a relatively good approximation of reality, neglecting some points that physically actually happen. Phenomena such as the occurrence of plasticity in the mold, variation of emissivity with temperature, creep, etc. are from other focus areas and can be studied and deepened in other works.

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